Quality and safety of broiler meat in various chilling systems

E. Demirok,* G. Veluz,† W. V. Stuyvenberg,‡ M. P. Castañeda,§ A. Byrd,# and C. Z. Alvarado†[1]

*Ankara University, Engineering Faculty, Department of Food Engineering, Ankara, Turkey 06110; †Texas A&M University, Department of Poultry Science, College Station 77843; ‡TopKip B. V., Enschede, the Netherlands 7546 PD; §Universidad Nacional Autónoma de México, Facultad de Medicina Veterinaria y Zootecnia, Centro de Enseñanza, Investigación y Extensión en Producción Avícola, México, D.F. México 04510; and #USDA-ARS, Southern Plains Agricultural Research Center, College Station, TX 77845

ABSTRACT Chilling is a critical step in poultry processing to attain high-quality meat and to meet the USDA-Food Safety and Inspection Service temperature standards. This study was conducted to determine the effects of commercially available chilling systems on quality and safety of broiler meat. A total of 300 carcasses in 2 replications were randomly selected from a commercial processor and subjected to 3 systems: immersion chill (IC), air chill (AC), and combi in-line air chill (CIAC). Incidence of *Salmonella* and *Campylobacter* were determined on pre- and postchilled carcasses. Quality of the meat was evaluated by carcass yield, drip loss, cook loss, texture, moisture content, sensory qualities, and color (L*, a*, and b*) of boneless skinless breast fillets and skin-on drums. Shelf life of whole carcasses, breast fillets, and drums was also determined. The IC resulted in the most reduction of *Salmonella* (39.7%) and *Campylobacter* (43%) incidence due to the washing effect and presence of chlorine in the chilled water. There was no significant difference in shelf-life when comparing the chilling methods. The IC had the highest ($P < 0.05$) carcass yield (6.5%), followed by CIAC (+1.98.0%) and then AC (−1.10%). Drip loss, cook loss, and moisture content of breast fillets were not significantly different for all the chilling systems, but higher L* value was observed for breast fillets at 24 h postmortem treated with IC and CIAC. However, IC exhibited the lightest color and AC was darkest in the drum samples. Shear force of breast meat was significantly more tender for AC and CIAC. There were no differences in the sensory qualities of breast fillets and drums among the 3 chilling systems.

Key words: immersion chilling, air chilling, combi in-line air chilling, broiler meat, pathogen bacteria

2013 Poultry Science 92:1117–1126
http://dx.doi.org/10.3382/ps.2012-02493

INTRODUCTION

In poultry processing, chilling is a crucial step that can prevent microbial growth to a level that will maximize both product safety and shelf life (Carroll and Alvarado, 2008). Generally, eviscerated carcasses are chilled by an immersion system, which is the most frequently used system in the United Stated because it is more efficient, or air chilling, which is more common in Europe, Brazil, and Canada (Fluckey et al., 2003; Carciofi and Laurindo, 2007; Huezo et al., 2007b; Berrang et al., 2008; Carroll and Alvarado, 2008).

Both chilling systems have advantages and disadvantages on broiler quality and safety. During immersion chilling, carcasses can absorb water (4 to 6%) through the skin and surrounding fat in contrast to air chilling where there is no moisture pickup and even a negative yield due to excessive moisture loss (James et al., 2006; Carciofi and Laurindo, 2007; Carroll and Alvarado, 2008). In air chilling, weight loss between 1 to 1.5% is common and can be as high as 3% depending upon the capacity and system requirements (James et al., 2006). Because of the moisture pick-up in immersion chilling, carcasses have higher drip loss, thaw loss, and cook loss properties and can have greater drip loss when packed in trays (Huezo et al., 2007b). Regarding product quality, immersion chilling improves appearance and color (Huezo et al., 2007b), whereas air chilling causes dehydration and discoloration on the surface of the carcasses (James et al., 2006). Additionally, Hale and Stadelman (1969), Hale et al. (1973), and Zenoble et al. (1977) reported various results that indicated effects of different chilling systems on meat flavor. Moreover, chilling time was also found to be more effective than chilling system on product texture (James et al., 2006).

Another concern with chilling systems is microbial quality of the poultry carcasses. Fecal material is the

Received May 23, 2012.
Accepted December 7, 2012.
[1]Corresponding author: calvarado@poultry.tamu.edu

primary vehicle for foodborne pathogens, and when present on prechill carcasses, the extensive bird-to-bird contact via immersion chilling can result in pathogen cross-contamination to other carcasses (Bailey et al., 1987; Bilgili et al., 2002). However, some researchers noted that total microbial load on broiler carcasses can be reduced in immersion chilling systems because of the washing effect from counter-current flow water, agitation, and chlorination (Dickens and Whittemore, 1995; Petrak et al., 1999; Bilgili et al., 2002). Previous studies have indicated that immersion chilling reduced the numbers of carcass-associated total aerobic bacteria, coliforms, *Escherichia coli, Salmonella*, and *Campylobacter* (Berrang and Dickens, 2000; Bilgili et al., 2002; Northcutt et al., 2003, 2008). For air chilling, cross-contamination may be decreased because carcasses are hung individually on the line depending upon the presence of water spray incorporated in the air chill system (Fluckey et al., 2003; James et al., 2006). Spraying carcasses during air chilling, which is not allowed in the European Union, can cause aerosols of bacteria that can spread from carcass to carcass due to the fans blowing in air-chilled systems (Mead et al., 2000). Moreover, some authors claimed that air-chilled products have better microbial quality than f immersion-chilled products because air chilling without water spray can injure or kill bacteria as a result of skin surface dehydration during chilling (Berrang et al., 2008; Carroll and Alvarado, 2008). Concerning system parameters, although chilling rates in an immersion system are usually far faster than those achieved in an air system, operating cost is the highest for immersion chill system (James et al., 2006), as well as water and sewer costs (Huezo et al., 2007b).

In recent years, a newly developed combi in-line air chilling system was introduced in the European Union market with the purpose of producing high-quality poultry carcasses by combining the benefits and reducing the disadvantages of air chilling and immersion chilling. This new chilling technology moves carcasses individually on the shackles of the transport chain while combining in-line counter-current water chilling via dip tanks followed by air chilling. Recent research has indicated that this combi system saves on water usage (up to 95%) and energy costs (up to 45%), unlike the immersion chilling system, which has the highest water usage and energy consumption. Combi in-line air chilling system has high chilling efficiency and produces a rapid decrease in carcass temperature. Products chilled with this sytem have long shelf life and high quality (http://www.topkip.com/).

Although many research studies have been conducted comparing immersion and air chilling on broilers, no previous research has been conducted on comparison of the current systems with the combi in-line air chilling system. Therefore, the objective of the present study was to compare the quality and safety parameters in broiler meat chilled using combi in-line, immersion, and air chilling systems.

MATERIALS AND METHODS

Sampling and Chilling

A total of 300 birds (150 birds/replication) were randomly collected from an in-line processing plant that has both air chilling and immersion chilling. The broiler carcasses were obtained from the same flock per replication. The scalding temperature was 57°C (135°F) for 2.5 min. The carcasses were removed from the processing line before the IOBW and individually tagged, weighed, and placed in sterile rinse bags (Fisherbrand Secure T, Labplas, Quebec, Canada). To determine the incidence of *Salmonella* and *Campylobacter* before chilling, 100 mL of buffered peptone water (**BPW**) were poured into each bag and samples were rinsed for 60 s according to the procedure of Musgrove et al. (2003). Following the carcass rinse, 50 carcasess each were immediately transferred to immersion chill (**IC**, treatment 1), no-spray air chill (**AC**, treatment 2), and combi in-line air chill (**CIAC**, treatment 3) lines.

For the IC treatment, the 100 carcasses were placed on a conveyor belt that dropped birds into the auger-type Morris chiller. The temperature of the chilling water was 0.5 to 1.1°C, and the red water for this chiller contained 5 mg/kg of free chlorine. Red water, a well-known term in the industry, means the recirculated water from the chiller where most chlorine testing occurs in processing facilities. The birds were exposed to air agitation during the first 25 min (7.62 m) of the chiller. The carcasses were immersed for a duration of 80 min. In AC treatment, each carcass was hung by the hocks on shackles in the commercial air chilling room. The air velocity in the room was 3.6 m/min with the temperature of 0°C and RH of 72%. The carcasses were exposed to a continuous cold air flow for 120 min. The CIAC treatment consisted of 2 steps. The 100 carcasses were initially dipped in a series of 4 prototype tanks containing cold water with a temperature of approximately 8, 5, 5, and 2°C, respectively. The carcasses were dipped back and forth in each tank for 20 s (first tank), 40 s (second tank), 80 s (third tank), and 80 s (fourth tank). The carcasses were allowed to drain for 30, 60, and 60 s after the first, second, and third dip, respectively. After the fourth dip was completed, the carcasses were hung by the hocks in the shackles and run on the bar in the same air chilling room with air-chilled carcasses. The air velocity in the room was 3.6 m/min with a temperature of 0°C and RH of 72%. The carcasses were chilled in continuous flow of cold air for 120 min.

After 80 min of IC, the 100 tagged postchilled carcasses were allowed to drip for 20 s. Then they were collected and placed in sterile rinse bag, weighed, and rinsed with 100 mL of BPW to determine the incidence of *Salmonella* and *Campylobacter*. After 120 min, carcasses were collected from AC and CIAC, weighed, and rinsed as indicated above. All rinsates were aseptically collected and placed individually in 250-mL Nalgene bottles. Twenty carcasses were separated from each

treatment for the shelf-life study. The rest of the carcasses (80 birds per treatment) were manually deboned at 6 h postmortem (**PM**) by the same deboning employee at the facility on single cone lines. Boneless skinless breast fillets and drums were weighed and placed seperately in polyethylene Ziploc brand storage bags (S.C. Johnson & Son Inc., Racine, WI). All carcasses, deboned meats, and rinsate samples were kept in the cooler (4°C) with ice and shipped overnight to Texas A&M University and Southern Plains Agricultural Research Center Food and Feed Safety Research Unit for analysis.

Enumeration of Salmonella and Campylobacter

Upon arrival of the rinsate samples (<4°C) at the Southern Plains Agricultural Research Center Food and Feed Safety laboratory, the rinsate samples were prepared for enumeration of *Campylobacter* and *Salmonella*. For enumeration, 10% of each group (n = 10) were sampled by adding 1 mL of the carcasss rinse to 3 serially diluted tubes (1:10, 1:100, 1:1,000) containing 9 mL each of sterile Butterfield's buffer solution (Difco Laboratories, Detroit, MI), spread on the appropriate selective agar, and incubated for the specific organisms as follows: *Salmonella* on Brilliant Green Agar (Difco Laboratories) and modified lysine iron agar (Oxoid, Unipath Ltd., Basingstoke, Hampshire, UK) incubated 24 h at 37°C; *Campylobacter* on Campy-cefex plates (Difco Laboratories) and incubated for 24 to 48 h at 42°C.

To determine the incidence of *Campylobacter*, 20 mL of carcass rinse was transferred to 20 mL of modified Bolton's broth (Neogen, Lansing, MI) and incubated for 4 h at 37°C, followed by 20 h at 42°C in a microaerobic environment (5% O_2, 10% CO_2, and 85% N_2). After enrichment, samples were streaked for isolation on Campy-ceflex plates and incubated for 24 to 48 h at 42°C in the microaerobic environment. Suspect *Campylobacter* colonies were confirmed as a member of the genus by microscopical examination of morphology and motility on a wet mount under phase contrast (100×). The morphologically confirmed *Campylobacter* was further characterized serologically using a latex-agglutination kit specific for *Campylobacter jejuni, Campylobacter coli*, and *Campylobacter lari* (Integrated Diagnostics Inc., Baltimore, MD).

In the case of *Salmonella,* an equal volume of concentrated (2×) tetrathionate broth base or Rappaport Vassiliadis (Difco Laboratories) broth per rinsate sample was added individually. Enriched samples were incubated at 37°C for 24 h and streaked for isolation on Brilliant Green Agar or modified lysine iron agar containing novobiocin. After 24 h incubation, typical *Salmonella* colonies were confirmed by biochemical test on triple sugar iron agar and lysine iron agar base (Difco Laboratories), as described (Andrews et al., 1992).

Shelf Life Study

Upon arrival of the samples (whole carcasses, boneless skinless breast fillets and skin-on drums) to the Texas A&M University Poultry Science laboratory (<4°C), aerobic plate counts (**APC**) were determined. Six packages including one whole carcass in each, 6 bags including 2 boneless skinless breast fillets in each and 6 bags including 2 drums in each were analyzed on d 0 (arrival at the TAMU facility) for each chilling treatment and replication. To prepare dilution, 100 mL of BPW was poured into the one package and shaken by hand for 1 min. From the rinsate, 1 mL was serially diluted and 1 mL aliquot was plated in APC petrifilm (3M Microbiology Products, St. Paul, MN). The APC petrifilms were counted after they were incubated at 37°C for 2 d. Microbiological analysis was performed on d 0, 5, and 10. Samples were kept in a cooler (4°C) for 10 d to determine shelf-life.

Quality Study

To determine whole carcass yield based upon chilling method, a yield study was conducted at the processing plant. A total of 100 carcasses were used for each chilling treatment for yield determination. The weight of the carcasses was determined by using digital hanging scale (AWS SR-20). The whole carcass yield was calculated according to the difference between prechill carcass weight and postchill carcass weight.

Commission Internationale de l'Eclairage L*, a*, and b* color measurements were performed on boneless skinless breast fillets and skin-on drums. The L* represents the degree of lightness (0 = black to 100 = white), a* represents green (−a*) to red (+a*), and b* represents blue (−b*) to yellow (+b*). Raw breast meat color was analyzed on the dorsal surface of the boneless skinless breast muscle at 6 h (n = 80) and 24 h (n = 50) PM using a Minolta Chroma Meter (model CR300, Ramsey, NJ) that was standardized with a white calibration plate (reference number 1353123; Y = 92.7; x = 0.3133; and y = 0.3193). Raw skin-on drum color was measured on the skin surface of the drum at 6 h (n = 80) and 24 h (n = 50) PM. Three color readings, each in triplicate, were conducted from a different location on each muscle and skin-on drum. Values for each color were averaged.

Drip loss analysis was performed on 50 bags containing 2 boneless skinless breast fillets in each and 50 bags containing 2 skin-on drums in each after 24 h PM. Breast fillets and drums were weighed right after deboning at 6 h PM. Then they were transferred to Texas A&M Laboratory in the shipping cooler with ice. Upon arrival of the samples, they were kept in the cooler at 4°C. At 24 h PM, tagged fillets and drums were removed from the bags one by one, dried with an individual paper towel, and weighed. Drip loss (%) was calculated according to the difference between first

weight of chicken parts measured at the facility and second weight of them measured after 24 h PM (Honikel, 1998). Moisture analysis was performed on the half of the raw breast fillets (n = 50). Total moisture was determined by the oven dry method (AOAC 950.46; AOAC International, 1998). For cook loss analysis in drums (n = 100) and boness skinless breast fillets (n = 100), samples were weighed individually, tagged (Dennison brand tagger, Kent, WA, and Weber brand label, Arlington Heights, IL) with a number, and placed on a wire rack. The rack was placed into a stainless steel tray. The tray was covered with an aluminum foil and baked in the convection oven (Blodgett Mark V-111, Blodget, Burlington, VA) at 350°F (177°C) to an internal temperature of 176°F (80°C). After the samples were allowed to cool in a covered aluminum foil lined pan, the cooked breast fillets and drums were weighed. Cook loss (%) of breast fillets and drums was calculated by dividing the weight loss during cooking by the raw weight and multiplying it by 100 (Sams, 1990). Half of the cooked breast samples (n = 50) were vacuum packaged and stored in a 4°C cooler (<72 h) until sensory analysis was performed. The remainder of the cooked breast fillets (n = 50) were also vacuum packaged and kept at 4°C until texture analysis was performed (<48 h). Duplicate samples (40 × 20 × 7 mm) from each cooked fillet were cut parallel to the direction of the muscle fibers, weighed, and then sheared for tenderness evaluation with an Instron Universal Testing Machine (Instron Corp., Canton, MA) using a 10-blade Allo-Kramer shear compression cell, a 454-kg load cell at 50% capacity, and a crosshead speed of 500 mm/min. For calculation of shear value, shear force value obtained in kg-force was transferred to Newtons; then this value was divided by the weight (g) of the sample (Sams, 1990). Shredded cooked breast samples (n = 50) were collected, and moisture analysis was conducted for cooked breast meat.

A total of 30 consumer panelists evaluated the sensory properties of cooked breast fillets and cooked drums. Separated vacuum packaged samples were taken out from the cooler and allow to reach room temperature on the day of sensory analysis. They were prepared according to the modified procedure of Jeong et al. (2011a). Each cooked breast and drum sample was cut into cubic form (approximately 2 × 2 cm) using a knife and a plastic template. The cubes were only taken from the cranial region of the breast fillets and fibula region of the drums. All pieces were put on a tray separately and placed into oven to warm up (40°C). Before serving, samples were taken out from the oven. One piece from each treatment was placed on a polyfoam tray and was assigned and labeled with a 3-digit random number and covered with aluminum foil to prevent cool-down. The tray, with 3 samples, was randomly presented to each panelist. Panelists consisted of male and female faculty, staff, and graduate and undergraduate students at Texas A&M University. Filtered water and unsalted crackers were provided for mouth cleansing between samples. Breast and drum samples were presented to panelists separately. The sensory facility had individualized booths, and samples were served through a hatch door. Panelists were asked to evaluate the samples for color, tenderness, juiciness, and overall flavor on a 9-point hedonic scale (color, 1 = extremely dark to 9 = extremely pale; tenderness, 1 = extremely tender to 9 = extremely tough; juiciness, 1 = extremely juicy to 9 = extremely dry; overall flavor, 1 = like extremely to 9 = dislike extremely). Panelists were also encouraged to make comments on their decisions.

Statistical Analysis

Bacterial counts from direct serial dilution plating were transformed to $\log_{10}$ cfu per milliliter of rinse recovered. Chi-squared procedure was conducted to analyze *Salmonella* and *Campylobacter* incidence in carcasses assuming IC samples were our control sample. For the other results, statistical analysis was performed using ANOVA and Duncan`s mean separation test to determine significance in each parameter between chilling treatments ($P < 0.05$). There was no trial × treatments interaction, so data were pooled within a parameter by treatment.

RESULTS AND DISCUSSION

Salmonella and Campylobacter Incidence

Poultry meat is an important source of food poisoning organisms, particularly *Campylobacter* and *Salmonella*. These pathogens survive in the intestinal tracts of chickens, which makes the task of eliminating them from poultry products difficult, and these pathogens can be detected on carcasses after processing (Fluckey et al., 2003; James et al., 2007). In our study, incidence in the prechill samples indicated that a total of 296 (99.7%) carcasses were found positive for *Salmonella* and 202 (68.0%) were positive for *Campylobacter* (Table 1). Only the control samples (IC) decreased *Salmonella* incidence significantly following the chi-squared analysis ($P < 0.05$). There was no significant difference between prechill and postchill AC and postchill CIAC *Salmonella* incidence. This lack of difference in both AC and CIAC samples could be due to the lack of long-term washing and agitation effects present in the immersion chiller. In addition, the red water used in the IC contained 5 mg/kg of chlorine, which could have helped in the decrease of *Salmonella* incidence. When analyzing the log/mL rinse results, there was a significant decrease from the prechill samples (1.82 log/mL rinse) to postchill samples. In addition, there was about a 0.5 log difference between the postchill IC samples and the postchill AC and CIAC samples. Even though there was a reduction in *Salmonella* incidence in the IC carcasses, the log/mL positive rinse was more than observed with other chilling systems. This increase observed in log/mL rinse in the IC may

Table 1. Incidences and microbial counts of *Salmonella* and *Campylobacter* in pre- and postchilled carcasses[1]

Item	Salmonella, +/total (%)	*Salmonella*, log/mL rinse	*Campylobacter*, +/total (%)	*Campylobacter*, log/mL rinse
Prechill	296/297 (99.7)***	1.82[a]	202/297 (68.01)***	4.36[a]
Postchill/IC (control)	60/100 (60)	0.68[ab]	25/100 (25)	1.00[c]
Postchill/AC	91/100 (91)***	0.11[b]	65/100 (65)***	3.01[b]
Postchill/CIAC	96/98 (98)***	0.11[b]	75/98 (76.53)***	2.46[b]

[a–c]Different letters indicate significant differences within groups ($P < 0.05$).

[1]n = 300 (prechill); n = 100 (postchill); n = 10/treatment [enumeration of *Salmonella* and *Campylobacter* (log/mL rinse)]. IC = immersion chill; AC = air chill; CIAC = combi in-line air chill.

***Chi square is significant at $P < 0.005$ for incidence of *Salmonella* and *Campylobacter*.

be due to the cross-contamination effect of long-term immersion chilling. Bacteria that are not fully attached to the skin of the broiler carcass can become detached during immersion chilling agitation and cross-contaminate other carcasses in the chiller (Bailey et al., 1987). Similar results were reported by Bilgili et al. (2002) who determined that IC reduced incidence of *Salmonella* from 20.7 to 5.7% on whole carcasses. However, there was no change in numbers of immersion-chilled *Salmonella*-positive carcasses in another study carried out by Cason et al. (1997).

Along with *Salmonella*, *Campylobacter* on poultry carcasses has recently become a USDA-Food Safety and Inspection Service performance standard in the United States. *Campylobacter* incidence was measured in this study to determine the effect of chilling systems on the incidence of this pathogen. A similar trend to that in *Salmonella* was observed for *Campylobacter* incidence. The incidence in the postchill IC samples was significantly lower compared with the prechill, postchill AC, and postchill CIAC following chi-squared analysis (Table 1). The decrease was expected in the IC due to the washing effect of the system and presence of chlorine (5 mg/kg in the red water) used in the chilling water. When comparing log/mL rinse among treatments, the results indicate that IC, which is considered the control, was significantly lower than the remaining treatment groups (prechill, postchill AC, postchill CIAC). There was a 0.5 log difference in the postchill CIAC compared with the postchill AC. It is important to note that the results regarding both air chilling systems could be due to the lack of antimicrobials used in the dipping water at the first step of the system. In contrast with our findings, Lindblad et al. (2006) reported that AC can be more effective than IC to lower the incidence of *Campylobacter* because AC can injure or kill *Campylobacter* by desiccation. However, IC was found to be more effective than AC in our study. Similarly, Berrang et al. (2008) reported that *Campylobacter* counts of half carcasses subjected to AC were approximately 0.5 log cfu/g higher than those subjected to the ice-water immersion chilling. Zhang et al. (2011) found broiler carcasses treated with air chilling had higher *Campylobacter* counts than those of treated with water immersion chilling because of the presence of chlorine in the chill water as observed in our study. Northcutt et al. (2008) determined that IC has provided great reduction in *Campylobacter* incidence but there was a slight decrease for *Salmonella*. In addition, Fluckey et al. (2003) reported no significant reductions in *Campylobacter* and *Salmonella* numbers on carcasses treated with an AC procedure in a commercial processing plant. From the previous research and the current study, it is evident that the efficacy of the system is variable depending upon the initial load of pathogens, type of system, capacity, cooling ability, among other factors. With that said, and concerning effects of CIAC system on control of pathogens, it is important to note that one of the significant benefits of this system is flexibility, which means that reduction in incidence of pathogens can be provided making minor changes in the system depending on the specific requirements of the countries. As an illustration, the approximately 4 min of immersion with CIAC system allows addition of antimicrobials in water, especially in United States, that could decrease pathogens in a commercial IC system. In addition, the CIAC system with agitation could be adopted by European Union facilities with no permission to use antimicrobials for chilling. In those facilities, utilization of proper agitation in the 4 min of immersion can provide a washing effect to decrease pathogens.

Shelf Life Study (APC)

Aerobic plate count is a good predictive indicator of product spoilage. Even though there are many quality factors that can determine spoilage, such as microbial growth, organoleptic changes, and endogenous enzymatic activity (Ellis et al., 2002), a general consensus of greater than 10^6 cfu/g in product is considered spoiled (Alvarez-Astorga et al., 2002). The aim of the whole carcasses APC analysis was to indicate shelf life of the intact product. The APC of whole carcasses from AC and CIAC systems were not different ($P > 0.05$) at d 0, 5, and 10 (Table 2). The carcasees from the IC system had a lower ($P < 0.05$) APC due to the probable washing effect of the system and presence of chlorine compared with the other chilling systems. The differences in APC were approximately 1 log cfu/mL on d 0, and 0.5 log cfu/mL on d 5 and 10. However, APC levels of meat samples from all treatments exceeded

the 10^6 cfu/mL at d 10, indicating spoilage. al-Mohizea et al. (1994) found 5 log increase during 14 d of storage at 4°C for air-chilled broiler carcasses packaged in polyethylene bags. In addition, Tuncer and Sireli (2008) reported that a 5.35 and 4.94 log increase was determined for air-chilled unpacked carcasses or those packaged in synthetic plate for 5 d of storage at 4°C. Also, they found 5.17 log increase for air-chilled carcasses packaged in polyethylene bags during 10 d of storage at 4°C. In the present study, a 2.95 log increase was indicated for air-chilled carcasses packaged in sterile rinse bags during 10 d of storage at 4°C. Regarding immersion-chilled broiler carcasses, Regez et al. (1988) reported 3.5 and 5.7 log increase at d 6 and 12 of storage at 4°C. Tuncer and Sireli (2008) determined 5.94, 5.35, and 4.91 log increment during 8 d of storage at at 4°C for immersion-chilled unpackaged carcasses, packaged in a synthetic plate or polyethylene bag. In the current study, APC of immersion-chilled carcasses was 3.78 log cfu/mL on d 0 (24 h PM) and 7.15 log cfu/mL on d 10. The increase was lower in our study compared with Regez et al. (1988) and Tuncer and Sireli (2008). Overall, the differences among the previous studies and our results were probably because of differences in the storage time, conditions of packaging, and initial bacterial load of carcasses.

For boneless skinless breast fillets on d 0 (24 h PM), samples subjected to CIAC had the highest APC count (3.88 log cfu/mL), followed by AC (3.57 log cfu/mL) and then IC (2.97 log cfu/mL). When comparing the AC and CIAC systems, there was less than a 0.5 log cfu/mL difference between the 2 treatments on d 0 ($P < 0.05$). This difference, even though statistically different, is minimal. The same trend was observed at d 5; even with the IC, APC counts were increasing for the AC samples. By d 10, all samples were considered spoiled and there were no differences ($P > 0.05$) in APC counts. It is expected that the IC carcasses have lower APC loads at 24 h PM and d 5 due to the antimicrobial effect of chlorine and washing effect of the system. In contrast to our results, Carroll and Alvarado (2008) reported air-chilled marinated breast fillets had lower APC than those immersion chilled during 12 d of storage due to cross-contamination effects of the immersion chill system. Shelf-life (APC) was also measured on drums to determine differences in shelf life from the skin-off product. However, the same results were observed on drums as in breast fillets for all days measured. On d 10, all samples APC counts reached greater than 10^6 cfu/mL, so they were considered spoiled.

Table 2. Aerobic plate counts (APC; log cfu/mL) of whole carcass rinse, rinse of boneless skinless breast fillets, and rinse of drums[1]

	APC results, log cfu/mL		
Item	Breast fillets	Drums	Carcasses
24 h PM (d 0)			
IC	2.97 ± 0.08[c]	3.08 ± 0.07[c]	3.78 ± 0.11[b]
AC	3.57 ± 0.13[b]	3.50 ± 0.13[b]	4.74 ± 0.08[a]
CIAC	3.88 ± 0.09[a]	3.72 ± 0.16[a]	4.69 ± 0.05[a]
d 5			
IC	3.11 ± 0.07[b]	3.57 ± 0.07[b]	3.86 ± 0.11[b]
AC	3.33 ± 0.02[b]	3.64 ± 0.13[b]	4.33 ± 0.03[a]
CIAC	3.80 ± 0.16[a]	4.01 ± 0.06[a]	4.32 ± 0.06[a]
d 10			
IC	6.44 ± 0.24[a]	7.49 ± 0.19[a]	7.15 ± 0.09[b]
AC	6.21 ± 0.45[a]	7.53 ± 0.14[a]	7.69 ± 0.16[a]
CIAC	6.47 ± 0.19[a]	7.85 ± 0.06[a]	7.70 ± 0.17[a]

[a–c]Different letters indicate significant differences within groups ($P < 0.05$).

[1]n = 6. PM = postmortem; IC = immersion chill; AC = air chill; CIAC = combi in-line air chill.

Quality Attributes

Results from carcass yield and physiochemical properties are summarized in Table 3. Yield is a critical component in processing plants and can be affected by chilling systems. Carcasses treated with IC had a highest significantly higher yield (+6.5%) than the CIAC (+1.98) followed by the AC (−1.10%). As expected, the most moisture pick-up was observed in immersion-chilled carcasses, whereas the AC carcasses lost some weight because of the dehydration effect during the process. Previous researches reported consistent results with this current study. Mielnik et al. (1999) determined average 2% weight loss in air-chilled carcasses. Perumalla et al. (2011) determined immersion chilling resulted in carcass weight gain by 3.94%; however, air chilling caused a reduction in carcass weight by −2.02%. Similar results were also reported by Huezo et al. (2007b), who reported average 2.5% weight loss and average 9.3% moisture pickup for air-chilled and immersion-chilled broilers, respectively. Zhuang et al. (2008) determined 2.4% reduction in weight of air-chilled broilers and 4.6% increase in weight of immersion-chilled broilers. Jeong et al. (2011b) noted that water-chilled carcasses picked up moisture at 4.6% and those air chilled lost 1.5% of their weight. Because the CIAC system used strategically placed dip tanks with 4 min of dip time, there was moisture pick-up in the carcass. It is important to remark that another significant benefit of the CIAC system is that the multi-tank system creates a controllable and flexible environment so that water pick-up and yield improvements can be maintained between 0 and 6%, depending on the number of dip tanks, the placement of the dip tanks, and the temperature of the water in the dip tanks. For this reason, the yield loss can be minimized and a target of 0% can be reached for the European Union market for air chill labeling requirements. For the US market, yield can be improved to 6% with slight modifications of the parameters listed above. The flexibility of the CIAC system is very unique and can provide yield improvements to plant-specific requirements.

Drip loss and cook loss are all indicators of meat moisture and yield retention. Most IC systems cause

Table 3. Average carcass yield and physico-chemical qualities (±SEM) of boneless skinless breast fillets and drums from carcasses chilled in various chilling systems[1]

	Chilling treatment		
Item	IC	AC	CIAC
Carcass yield, %	+6.5 ± 1.00[a]	−1.10 ± 0.13[c]	+1.98 ± 0.15[b]
Drip loss, %			
Breast fillets	2.33 ± 0.18	2.12 ± 0.22	2.08 ± 0.19
Drums	1.27 ± 0.15[a]	0.70 ± 0.1[b]	1.03 ± 0.13[ab]
Cook loss, %			
Breast fillets	26.52 ± 0.81	26.17 ± 0.67	25.79 ± 0.53
Drums	22.79 ± 1.23[a]	14.68 ± 0.56[c]	19.63 ± 0.74[b]
Shear force value, N			
Breast fillets	36.78 ± 1.00[a]	31.82 ± 0.63[b]	33.48 ± 0.58[b]
Moisture, %			
Raw breast fillets	75.05 ± 0.28	74.54 ± 0.16	75.11 ± 0.20
Cooked breast fillets	67.88 ± 0.39	68.15 ± 0.29	68.35 ± 0.31

[a–c]Means with same letter within a row are not statistically different ($P < 0.05$).

[1]n = 100 (carcass yield, cook loss, shear value); n = 50 (drip loss, raw and cooked moisture). IC = immersion chill; AC = air chill; CIAC = combi in-line air chill.

water to be absorbed in the intercellular spaces created during rigor motris (Carciofi and Laurindo, 2007). However, this water absorption is not normally retained following chilling, especially during the cut-up process. Therefore, the yield pick-up is not a true gain. In this study, there was no significant difference ($P > 0.05$) in 24 h PM drip loss or cook loss in the breast fillets (Table 3). However, the IC drums had the highest drip loss and cook loss as expected, possibly due to the water absorbed by the skin and surrounding fat. Combi in-line air-chilled drums had higher drip loss and cook loss percentages than AC because the carcasses were dipped into dip tanks for a total of 4 min during the early stages of chilling. These findings were consistent with a previous report by Zhuang et al. (2008), which found that drip loss and cook loss of immersion-chilled breasts did not differ from air-chilled breasts. On the other hand, Jeong et al. (2011b) noted immersion-chilled breasts and drums had a significantly higher drip loss than those of air chilled ($P < 0.05$). Generally, drip loss and cook loss in breast fillets were higher than drums regardless of chilling system applied because drums have higher fat content and keep moisture in the skin and between the fat globules.

Shear value is an indicator of objective tenderness in poultry breast meat, and tenderness is one of the key factors in consumer satisfaction for eating quality. The higher the shear force value, the tougher the meat (Owens and Meullenet, 2010). Breast fillets from carcasses subjected to IC system had significantly higher ($P < 0.05$) shear force value (36.78 N) than those subjected to AC (31.82 N) and CIAC (33.48 N), indicating less tender meat. However, no difference in tenderness was seen between AC and CIAC samples (Table 3). A recent similar study by Carroll and Alvarado (2008) observed that marinated air-chilled breast fillets were found more tender than those that were immersion chilled. In contrast to our results, Huezo et al. (2007b) reported that there was no significant differences between shear force value of marinated air-chilled or immersion-chilled cooked breast fillets. Besides, Huezo et al. (2007a) determined in another study that neither immersion chilling or air chilling differed in shear force value of breast fillets at 24 h PM. The differences between our results and Huezo et al. (2007a,b) probably resulted from deboning time and marination process because these 2 factors as well as age, genetic strain, rigor development, and cooking methods, can affect tenderness of poultry meat (Owens and Meullenet, 2010; Perumalla et al., 2011).

Meat moisture is important in determining tenderness and eating quality for consumers (Owens and Meullenet, 2010). In the present study, none of the chilling treatments affected moisture content of raw and cooked breast fillets at 24 h PM even though there were differences in tenderness (Table 3). Tenderness is affected by many factors mentioned above, whereas moisture content depends on water-holding capacity of meat, and this capacity is affected by the ultimate pH value occurred as a result of rigor development in meat (Owens and Meullenet, 2010). In addition, Jeong et al. (2011a) reported that immersion-chilled breast fillets lost absorbed water that gained during chilling overnight storage; therefore, no differences were found among immersion, air, or evaporative air-chilled breast fillets. Similarly, Young and Smith (2004) determined that water-chilled carcasses absorbed an average of 11.7% moisture in the chiller, of which 4.72% was lost within 24 h of intact carcass storage, 0.98 was lost in debonning, and 2.10% was lost in storage of chicken parts; however, no significant changes in moisture content of air-chilled carcasses were observed during intact carcass storage, deboning, and storage of chicken parts. According to these previous studies (Young and Smith, 2004; Jeong et al., 2011a), immersion-chilled carcasses lost excess moisture absorbed in the chiller during cut-up operations and storage of intact carcass or chicken parts after postchilling. In the current study, there were no significant differences among treatments regarding moisture content after 24 h PM, and our findings were

Table 4. Average lightness (L*), redness (a*), and yellowness (b*) values (±SEM) of boneless skinless breast fillets and drums[1]

	Chilling treatment		
Item	IC	AC	CIAC
Breast, 6 h PM			
L*	55.37 ± 0.29^{ab}	56.44 ± 0.71^{a}	54.49 ± 0.37^{b}
a*	2.80 ± 0.14^{b}	3.35 ± 0.21^{a}	3.02 ± 0.12^{ab}
b*	5.70 ± 0.21^{a}	4.68 ± 0.28^{b}	4.96 ± 0.24^{b}
Breast, 24 h PM			
L*	68.86 ± 1.72^{a}	55.85 ± 0.95^{b}	67.66 ± 1.63^{a}
a*	2.54 ± 0.17	2.48 ± 0.10	2.65 ± 0.15
b*	7.28 ± 0.59^{a}	5.24 ± 0.29^{c}	6.36 ± 0.63^{b}
Drum, 6 h PM			
L*	71.73 ± 0.42^{a}	68.57 ± 0.53^{c}	70.06 ± 0.44^{b}
a*	2.68 ± 0.32^{b}	3.60 ± 0.25^{a}	2.70 ± 0.14^{b}
b*	4.87 ± 0.30^{a}	3.35 ± 0.34^{b}	4.13 ± 0.43^{ab}
Drum, 24 h PM			
L*	87.01 ± 2.25^{a}	82.83 ± 2.24^{c}	85.70 ± 2.36^{b}
a*	1.90 ± 0.16^{b}	2.83 ± 0.19^{a}	2.51 ± 0.14^{a}
b*	3.67 ± 0.46^{a}	1.88 ± 0.56^{b}	2.73 ± 0.36^{ab}

$^{a–c}$Means with same letter within a row are not statistically different ($P < 0.05$).

[1]n = 80 (6 h PM); n = 50 (24 h PM). IC = immersion chill; AC = air chill; CIAC = combi in-line air chill; PM = postmortem.

also in agreement with Zhuang et al. (2008) and Jeong et al. (2011b).

Color is a critical food quality attribute because it affects consumers' initial selection of a raw meat product in the marketplace (Fletcher, 1999). Color values of breast fillets and drums are summarized in Table 4. The L* value indicates lightness, +a* indicates redness, and +b* indicates yellowness color coordinates. Of these color parameters, L* is probably the most important in poultry because consumers can detect and discriminate lightness values easier than the other values (Guidi and Castigliego, 2010). Lighter or darker values from what consumers consider normal are unappealing and can affect purchasing power. In commercial AC systems, the color of the carcass and sometimes the meat is greatly affected and appears dark and dry, which can be unappealing to consumers (James et al., 2006). In our findings, the L* values of boneless skinless breast fillets from the CIAC and IC system were not different ($P > 0.05$) at 6 and 24 h PM but were found to be lighter ($P < 0.05$) than the AC system, especially at 24 h PM (Table 4). This result is similar to Carroll and Alvarado (2008), who found that air-chilled fillets were darker than immersion-chilled fillets after 24 h PM. No difference ($P > 0.05$) in L* values was seen between of air- and immersion-chilled fillets at 6 h PM; however, breast fillets from the IC system were lighter than those of AC at 24 h PM ($P < 0.05$). Even though there were differences in a* and b* values of breast fillets in the present study, these are much less significant to consumer perception of good quality. For redness at 6 h PM, the a* value of air-chilled breast fillets was found to be the highest, and this value was statistically different from the IC result ($P < 0.05$). For yellowness at 6 h PM, IC breasts had a higher b* value than AC breasts ($P < 0.05$), and CIAC breasts showed an intermediate value. Our findings showed that a* values of breast fillets decreased, whereas b* values increased after 24 h of storage. In contrast to our results, previous researchers (Jeong et al., 2011a) reported that immersion-chilled breast was significantly lighter than air-chilled breast at 5 h PM. They also reported that air-chilled breast samples had the highest a* and b* values. Zhuang et al. (2009) indicated that L*, a*, and b* values of immersion and air-chilled breasts did not differ from each other.

The skin on the drums from the AC system appeared darker ($P < 0.05$) than the other chilling systems due to the drying effect (Table 4). Dryness affects carcass light reflectance and skin color. Skin becomes thin and background color increases redness and yellowness as a result of dehydration (Huezo et al., 2007b). The CIAC system produced skin color in the drums that was significantly lighter ($P < 0.05$) than the AC system and significantly darker ($P > 0.05$) than the IC system at 6 and 24 h PM. This indicates that the skin in the CIAC carcasses retained more moisture during the chilling process compared with the AC, which produced skin that was darker in appearance. These findings agreed with Jeong et al. (2011b), who reported that air-chilled drums were darker than those of water and evaporative air chilling. In the present study, whereas skin color of IC drums had the lowest a* and the highest b* values, AC drums had a reverse situation at 6 h PM. Combi in-line air-chilled drums had also intermediate values. After 24 h of storage, L* values increased in all treatments, whereas a* and b* values decreased. Skin color of drums was found to be significantly darker in AC samples compared with IC or CIAC. Huezo et al. (2007b) who found that L* value decreased for immersion-chilled skin-on breast fillets, whereas it increased for air-chilled fillets after 24 h of aging. However, they similarly reported that immersion-chilled samples had lighter color than those that were air chilled. In our

study, color results of CIAC drums also changed at 24 h PM and showed statistically significant differences from the other 2 chilling systems. Overall, when comparing a* values of all 3 chilling systems, a* values of IC breast fillets and drums at 6 and 24 h PM were lower than others. Loss of some of the epidermis during immersion chilling due to agitation, washing effect, and carcass-to-carcass contamination can be a reason for this result (Huezo et al., 2007b).

Cooked breasts and drums were evaluated by 30 panelists related to color, tenderness, juiciness, and overall flavor properties. There were no significant differences ($P > 0.05$) among the 3 different chilling systems for cooked breast samples for all the parameters (data not shown). Similar results were reported by Zhuang et al. (2009) and Jeong et al. (2011a). Even though there were significant differences ($P < 0.05$) in shear force values for sensory attributes of tenderness between IC and AC or IC and CIAC, these differences were not detected by the sensory panelists. No statistical differences were also observed among the 3 different chilling systems for all the sensory attibutes of cooked drums (data not shown).

In conclusion, the combi in-line air chilling system was comparable with the current immersion chill system, the most frequently used system in the United States, when considering quality and safety.

ACKNOWLEDGMENTS

Appreciation is expressed to Pilgrim's Pride Company (Live Oak, FL) members who offered an opportunity to design our experiment at their facility and TopKip USA, LLC (Enschede, the Netherlands) for sharing their experiments.

REFERENCES

al-Mohizea, I. S., A. S. Mashhadi, A. Fawwal, and A. Al-Shalhat. 1994. Microbiological and shelf life assessment of chilled eviscerated whole chicken broilers in Saudi Arabia. Br. Poult. Sci. 35:519–526.

Alvarez-Astorga, M., R. Capita, C. Alonso-Calleja, B. Moreno, and M. C. Garcia-Fernandez. 2002. Microbiological quality of retail chicken by-products in Spain. Meat Sci. 62:45–50.

Andrews, W. H., V. R. Bruce, G. June, F. Satchell, and P. Sherrod. 1992. *Salmonella*. Pages 51–69 in Bacteriological Analytical Manual, 7th ed. AOAC Int., Arlington, VA.

AOAC International. 1998. Official Methods of Analysis of AOAC International. 5th ed. AOAC Int., Gaithersburg, MD.

Bailey, J. S., J. E. Thompson, and N. A. Cox. 1987. Contamination of poultry during processing. Page 193 in The Microbiology of Poultry Meat Products. F. E. Cunningham and N. A. Cox, ed. Acad. Press, New York, NY.

Berrang, M. E., and J. A. Dickens. 2000. Presence and level of *Campylobacter* on broiler carcasses throughout the processing plant. J. Appl. Poult. Res. 9:43–47.

Berrang, M. E., R. J. Meinersmann, D. P. Smith, and H. Zhuang. 2008. The effect of chilling in cold air or ice water on the microbiological quality of broiler carcasses and the population of *Campylobacter*. Poult. Sci. 87:992–998.

Bilgili, S. F., A. L. Waldroup, D. Zelenka, and J. E. Marion. 2002. Visible ingesta on prechill carcasses does not affect the microbiological quality of broiler carcasses after immersion chilling. J. Appl. Poult. Res. 11:233–238.

Carciofi, B. A. M., and J. B. Laurindo. 2007. Water uptake by poultry carcasses during cooling by water immersion. Chem. Eng. Process. 46:444–450.

Carroll, C. D., and C. Z. Alvarado. 2008. Comparison of air and immersion chilling on meat quality and shelf life of marinated broiler breast fillets. Poult. Sci. 87:368–372.

Cason, J. A., J. S. Bailey, N. J. Stern, A. D. Whittemore, and N. A. Cox. 1997. Relationship between aerobic bacteria, *Salmonellea* and *Campylobacter* on broiler carcasses. Poult. Sci. 76:1037–1041.

Dickens, J. A., and A. D. Whittemore. 1995. The effects of extended chilling times with acetic acid on the temperature and microbiological quality of processed poultry carcasses. Poult. Sci. 74:1044–1048.

Ellis, D. I., D. Broadhurst, D. B. Kell, J. J. Rowland, and R. Goodacre. 2002. Rapid and quantitative detection of the microbial spoilage of meat by fourier transform infrared spectroscopy and machine learning. Appl. Environ. Microbiol. 68:2822–2828.

Fletcher, D. L. 1999. Broiler breast meat color variation, pH, and texture. Poult. Sci. 78:1323–1327.

Fluckey, W. M., M. X. Sanchez, S. R. Mckee, D. Smith, E. Pendleton, and M. M. Brashears. 2003. Establishment of a microbiological profile for an air-chilling poultry operation in the united states. J. Food Prot. 66:272–279.

Guidi, A., and L. Castigliego. 2010. Poultry meat color. Pages 359–388 in Handbook of Poultry Science and Technology, Volume 2: Secondary processing. I. Guerrero-Legarreta and Y. H. Hui, ed. Wiley Publishing, Indianapolis, IN.

Hale, K. K., and W. J. Stadelman. 1969. Flavour differences between wet-chilled and dry chilled broilers. Poult. Sci. 48:1814–1815.

Hale, K. K., W. J. Stadelman, and V. D. Bramblett. 1973. Effect of dry chilling on the flavour of fried chicken. Poult. Sci. 52:253–262.

Honikel, K. O. 1998. Reference methods for the assesment of physical characteristics of meat. Meat Sci. 49:447–457.

Huezo, R., J. K. Northcutt, D. P. Smith, and D. L. Fletcher. 2007a. Effect of chilling method and deboning time on broiler breast filet quality. J. Appl. Poult. Res. 16:537–545.

Huezo, R., D. P. Smith, J. K. Northcutt, and D. L. Fletcher. 2007b. Effect of immersion or dry air chilling on broiler carcass moisture retention and breast fillet functionality. J. Appl. Poult. Res. 16:438–447.

James, C., S. J. James, N. Hannay, G. Purnell, C. Barbedo-Pinto, H. Yaman, M. Araujo, M. L. Gonzalez, J. Calvo, M. Howell, and J. E. L. Corry. 2007. Decontamination of poultry carcasses using steam or hot water in combination with rapid cooling, chilling or freezing of carcass surfaces. Int. J. Food Microbiol. 114:195–203.

James, C., C. Vincent, T. I. Andrade Lima, and S. J. James. 2006. The primary chilling of poultry carcasses—A review. Int. J. Refrig. 29:847–862.

Jeong, J. Y., K. K. Janardhanan, A. M. Booren, J. B. Harte, and I. Kang. 2011a. Breast meat quality and consumer sensory properties of broiler carcasses chilled by water, air, or evaporative air. Poult. Sci. 90:694–700.

Jeong, J. Y., K. K. Janardhanan, A. M. Booren, D. M. Karcher, and I. Kang. 2011b. Moisture content, processing yield, and surface color of broiler carcasses chilled by water, air, or evaporative air. Poult. Sci. 90:687–693.

Lindblad, M., I. Hansson, I. Vagsholm, and R. Lindqvist. 2006. Post-chill *Campylobacter* prevalence on broiler carcasses in relation to slaughter group colonization level and chilling system. J. Food Prot. 69:495–499.

Mead, G. C., V. M. Allen, C. H. Burton, and J. E. L. Corry. 2000. Microbial cross-contamination during air chilling of poultry. Br. Poult. Sci. 41:158–162.

Mielnik, M. B., R. H. Dainty, F. Lundby, and J. Mielnik. 1999. The effect of evaporative air chilling and storage temperature on quality and shelf life of fresh chicken carcasses. Poult. Sci. 78:1065–1073.

Musgrove, M. T., N. A. Cox, M. E. Berrang, and M. A. Harrison. 2003. Comparison of weep and carcass rinses for recovery

of *Campylobacter* from retail broiler carcasses. J. Food Prot. 66:1720–1723.

Northcutt, J. K., M. E. Berrang, J. A. Dickens, D. L. Fletcher, and N. A. Cox. 2003. Effect of broiler age, feed withdrawal, and transportation on levels of coliforms, *Campylobacter*, *Escherichia coli* and *Salmonella* on carcasses before and after immersion chilling. Poult. Sci. 82:169–173.

Northcutt, J. K., D. Smith, R. I. Huezo, and K. D. Ingram. 2008. Microbiology of broiler carcasses and chemistry of chiller water as affected by water reuse. Poult. Sci. 87:1458–1463.

Owens, C. S., and J. F. C. Meullenet. 2010. Poultry meat tenderness. Pages 491–514 in Handbook of Poultry Science and Technology, Volume 1: Primary Processing. Chapter 26. I. Guerrero-Legarreta and Y. H. Hui, ed. Wiley Publishing, Indianapolis, IN.

Perumalla, A. V. S., A. Saha, Y. Lee, J. F. Meullenet, and C. M. Owens. 2011. Marination properties and sensory evaluation of breast fillets from air-chilled and immersion-chilled broiler carcasses. Poult. Sci. 90:671–679.

Petrak, T., Z. Kalodera, P. Novakovic, and L. Gumhalter Karolyi. 1999. Bacteriological comparison of parallel and counter flow water chilling of poultry meat. Meat Sci. 53:269–271.

Regez, P., L. Gallo, R. E. Schmitt, and W. Schmitt-Lorenz. 1988. Microbial spoilage of refrigerated fresh broilers. III. Effect of storage temperature on the microbial association of poultry carcasses. Lebenson. Wiss. Technol. 21:229–233.

Sams, A. R. 1990. Electrical stimulation and high temperature conditioning of broiler carcasses. Poult. Sci. 69:1781–1786.

Tuncer, B., and U. T. Sireli. 2008. Microbial growth on broiler carcasses stored at different temperatures after air- or water-chilling. Poult. Sci. 87:793–799.

Young, L. L., and D. P. Smith. 2004. Moisture retention by water- and air-chilled chicken broilers during processing and cutup operations. Poult. Sci. 83:119–122.

Zenoble, O. C., J. A. Roberts, and F. E. Cunningham. 1977. Eating quality of spent hens processed with and without immersion chilling. Poult. Sci. 56:843–845.

Zhang, L., J. Y. Jeong, K. K. Janardhanan, E. T. Ryser, and I. Kang. 2011. Microbiological quality of water immersion-chilled and air chilled broilers. J. Food Prot. 74:1531–1535.

Zhuang, H., E. M. Savage, D. P. Smith, and M. E. Berrang. 2008. Effect of dry-air chilling on Warner-Bratzler shear force and water holding capacity of broiler breast meat deboned four hours postmortem. Poult. Sci. 7:743–748.

Zhuang, H., E. M. Savage, D. P. Smith, and M. E. Berrang. 2009. Effect of dry-air chilling on sensory descriptive profiles of cooked broiler breast meat deboned four hours after the initiation of chilling. Poult. Sci. 88:1282–1291.